INITIATION MECHANISM OF PULSED SURFACE FLASHOVER ALONG SILICON IN VACUUM BY PRE-BREAKDOWN CONDUCTION AND PHOTON EMISSION

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Abstract: Pre-breakdown (leakage) and breakdown currents and photon-emission associated with the currents, under impulse (0.36/10 μs) voltage stress, along high purity (ρ>30 KΩ cm) silicon, with and without gold end contacts in vacuum ($\sim 10^{-6}$ Torr), are discussed. Three distinct phases leading to the breakdown condition are observed. These are one-carrier (hole) leakage current, two-carrier (electrons and holes) current, and complete surface flashover processes. The onset of photon-emission coincides with the onset of two-carrier current. The temporally resolved one-carrier leakage current (ohmic or charge injection dominated) and photon-emission data show that there is a certain threshold leakage current which initiates the rest of the processes.

INTRODUCTION

Photoconductive switches have the potential to operate as ideal switches in many pulse power applications. However, surface flashover along photoconducting materials is presently the limiting factor in pulsed high voltage devices using such materials in their ability to reach voltage hold-off levels approaching their intrinsic breakdown strengths. At present, the dominant parameters which contribute to the flashover mechanism have not been identified. As a consequence, the purpose of this investigation is to identify experimentally the dominant parameters that contribute to the pulsed surface flashover in vacuum along high purity silicon.

EXPERIMENTAL

The experimental details are given in references 1 and 2. Tests are carried out in a stainless steel vacuum chamber, evacuated to 10^{-6} Torr. Impulses (0.39/10 μs) are applied across a high purity silicon sample (resistivity, ρ>30 kΩ cm) in the form of a circular cylinder with 25 mm diameter and 10 mm height. Samples are lightly doped (0.02 PPB) with Boron (p-type). Two different types of contacts are tested: gold end contacts (1 μm thick) and no contacts (plain silicon end), i.e., the specimen makes plain butt contacts with the electrodes, made of stainless steel. Voltage waveforms are monitored by an E-dot voltage probe. A Rogowski coil and a 50 Ω current viewing resistor (CVR) are used to monitor the breakdown and pre-breakdown currents, respectively. A photo-multiplier tube (PMT – 160 nm to 650 nm) is used to observe high energy (>1.91 eV) photon emission.

RESULTS

Fig. 1 shows a typical waveform of the three distinct processes leading to surface flashover of a high purity silicon specimen with gold contacts. Each of the distinct phases is indicated in the figure by I, II, and III.

The first process (interval I) represents the pre-breakdown conduction stage and will be called phase I. Phase I can be seen without subsequent II and III processes at voltages below breakdown. During this phase, the current reveals three different characteristics depending on the type of end contacts: ohmic dominant current or charge injection [space charge limited (SCL)] dominant current for

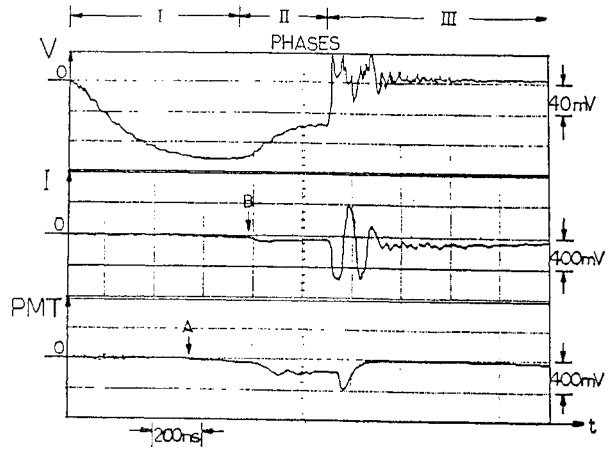

Fig. 1 Three distinct processes leading to flashover along high purity silicon with gold contacts. (V = 8.85 kV peak, I = 136 A peak, and PMT = 22.6 x 10^{-6} lm peak)
A = onset of photon emission
B = onset of phase II

specimens with gold end contacts [1], or pure charge injection (or pure SCL) for specimens with no end contacts (plain silicon ends) [2].

In the ohmic dominant phase I domain, the leakage current and applied impulse voltage do not show any time delay between their peaks, as shown in Fig. 2. The current peak exhibits a linear dependence on voltage. With the ohmic dominant leakage current, no photon emission was detected with the PMT. This type of phase I behavior was generally observed for a specimen with gold contacts, prior to any breakdown.

In the SCL dominant phase I domain, the leakage current peak is delayed by about 4.5 μs from the applied voltage peak as shown in Fig. 3. This current peak exhibits a square dependence on the voltage peak (V^2). Occasional photon emission is detected by the PMT in this phase. Ohmic current can be observed at the initial front of the SCL dominant current waveform. Hence this charge injection dominant current can be considered as a superposition of an ohmic component on the pure SCL current. This type of phase I behavior was observed for a specimen with gold contacts.

In the pure SCL phase I domain, the current peak is delayed about 8.8 μs from the applied voltage peak as shown in Fig. 4. The current peak exhibits a square dependence on voltage peak (V^2). PMT data are not yet available for specimens without contacts.

When the SCL dominant phase I leakage current reaches a certain threshold value, onset of photon emission occurs (point A in Fig. 1). From that instant, a steady increase of current and photon emission is detected [1]. After a certain time, a significant increase

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1989	**N/A**	**-**

4. TITLE AND SUBTITLE
Initiation Mechanism Of Pulsed Surface Flashover Along Silicon In Vacuum By Pre-Breakdown Conduction And Photon Emission

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering University of South Carolina Columbia, SC 29208

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT
Pre-breakdown (leakage) and breakdown currents and photon-emission associated with the currents, under impulse (0.36!10 IJ-S) voltage stress, along high purity (p>30 KQ em) silicon, with and without gold end contacts in vacuum (-lQ-6 Torr), are discussed. Three distinct phases leading to the breakdown condition are observed. These are one-carrier (hole) leakage current, two-carrier (electrons and holes) current, and complete surface flashover processes. The onset of photon-emission coincides with the onset of two-carrier current. The temporally resolved one-carrier leakage current (ohmic or charge injection dominated) and photon-emission data show that there is a certain threshold leakage current which initiates the rest of the processes.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**3**	

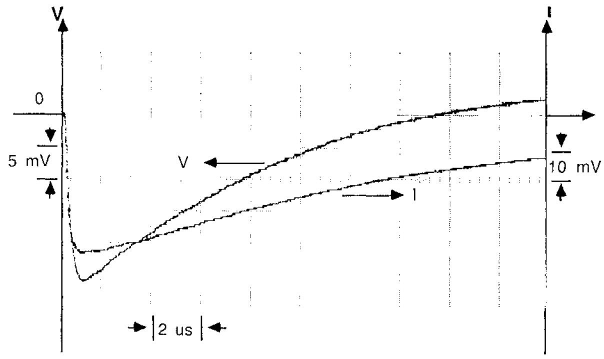

Fig. 2. Voltage (2.27 kV peak) and phase I ohmic dominant leakage current (0.17 A peak) for a specimen with gold contacts. No time shift between voltage and current peaks.

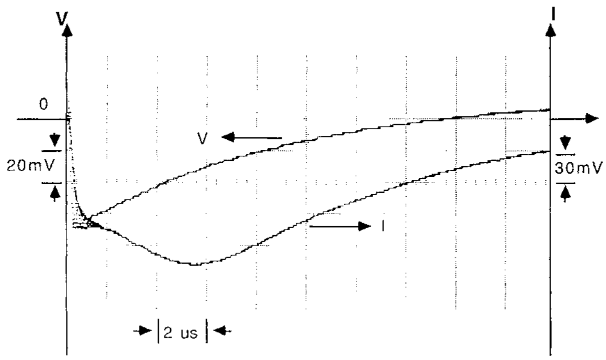

Fig. 3. Voltage (5.56 kV peak) and phase I SCL dominant leakage current (0.56 A peak) for a specimen with gold contacts. Time shift between V and I peaks is about 4.5 μs.

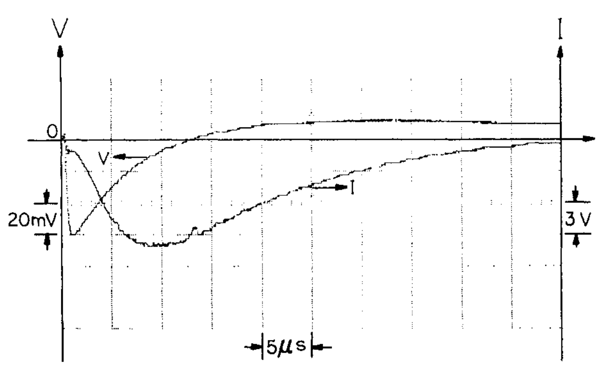

Fig. 4. Voltage (5.21 kV peak) and phase I pure SCL leakage current (1.27 A peak) for a sample with plain end contacts. Time shift between V and I peaks is about 8.8 μs.

of current and photon emission occurs (point B in Fig. 1), and concurrently an appreciable partial voltage collapse is detected. The process involving partial voltage collapse is defined as phase II (interval marked II in Fig. 1). Phases I and II alone, without subsequent III, are observed only occasionally for specimens with gold contacts [1]. However, for samples with plain end contacts, a distinct phase II process is observed over a range of applied voltages [2]. For such specimens, during phase II, the current and voltage are in time phase, and the current peak shows $V^{7.3}$ dependence where V represents the peak applied voltage in kV [2].

The final process (interval III in Fig. 1 and defined as phase III) is surface flashover and can be identified with a complete collapse of voltage. As can be seen in Fig. 1, the current and photon emission peaks reach maximum values corresponding to complete voltage collapse. Direct transition from phases I to III, without the intermediate phase II process, is also observed [2].

DISCUSSION

There are four major observations made in our experiment: leakage currents with no or negligible photon emission; the onset of photon emission at a threshold leakage current; partial voltage collapse with increased current amplitude and massive photon emission; and final surface flashover process.

Since silicon samples used here are p-type, the ohmic dominant current is mainly due to thermally generated free holes. It is reasonable to expect negligible or no photon emission activity during ohmic conduction because of equilibrium condition. In addition, gold contacts for silicon act as ohmic contacts for holes and blocking contacts for electrons [3]. Therefore, during pure SCL or SCL dominant conduction, only holes are efficiently injected from the anode. One-carrier SCL current generally has a square dependence on voltage (V^2) [4]. Since only single carriers (holes) are injected, and no electrons are injected efficiently from the cathode, photon emission due to indirect (phonon-assisted) or direct radiative recombinations is rarely detected using the PMT during the SCL dominant leakage current flow. Negligible photon emission is also expected during pure SCL current flow. We intend to verify the above prediction in the near future.

As discussed in the previous section, photon emission is detected only when the phase I leakage current reaches a certain threshold value near the applied voltage peak. Since significant radiative recombinations are expected only when there exist excess double carriers (electrons and holes), the onset of photon emission implies the onset of electron injection from the cathode. Since the electron injection is initiated when the leakage current reaches a certain threshold value at or near the voltage peak, we may say that the blocking potential barrier for electrons at the cathode contact are narrowed by accumulated space charges and also by the applied electric field. In other words, the threshold current and the peak applied voltage set the condition for electrons to efficiently tunnel through the barrier quantum mechanically.

A continuous supply of carriers from the electrodes and the generation of free carriers by absorption of photons within the material will eventually lead to partial voltage collapse, which is the phase II process. Similar results of the onset of double injection and photon emission are reported for organic semiconductors with dc [5] and ac [6] excitation, and the double carrier current is proportional to V^n, where V is the applied voltage and n is a real number which is greater than 6. For our silicon sample with plain contacts, n is 7.3.

The cylindrical surface of the semiconductor specimen where surface flashover occurs is generally expected to have a large density of localized states within the forbidden gap. These localized states can act as trap or recombination centers. In addition, surfaces have a higher probability of absorbing photons than the bulk because of the localized states. This high probability of absorption results in the transfer of energy from the bulk to the surface. Eventually the density of free carriers at the surface, generated by absorbing photons, will be more than that in the bulk. Surface flashover is believed to occur only through a certain filamentary channel in which there is an efficient absorption of the photons emitted from the bulk during double injection.

CONCLUSION

There are four major observations in this study. The first observation concerns leakage currents, which reveal three distinct characteristics, depending on the type of contact and the experimental conditions: ohmic dominant, SCL dominant, or pure SCL currents. All of these leakage currents are due to majority carriers (holes),

and no or negligible photon emission is detected because only one carrier is responsible for the conduction in this phase. The second observation is the onset of photon emission. At a certain threshold leakage current near the voltage peak, the onset of photon emission takes place. Photon emission is indicative of two-carrier conduction, implying that electrons are injected from the cathode by quantum mechanical tunnelling. The threshold current also indicates that a certain amount of space charge accumulation near the cathode at or near the instant of voltage peak is necessary to initiate the electron injection. The third observation is partial voltage collapse with increased current amplitude and massive photon emission, which is indicative of a well-developed two-carrier conduction process. The final step is surface flashover. The specimen surface, characterized by high density of localized states, efficiently absorbs photons emitted from the bulk, resulting in the generation of high density of carriers and leading to breakdown.

ACKNOWLEGEMENT

This work was sponsored by SDIO/IST and managed by ONR.

REFERENCES

1.- S.H. Nam and T.S. Sudarshan, "Effect of leakage current and light emission on surface flashover along silicon in vacuum", To be published in the Proc. 6th Int. Sym. on High Voltage Engineering, New Orleans, LA, USA, Aug. 1989.

2 - S.H. Nam and T.S. Sudarshan, "Observation of three distinct phases leading to pulsed surface flashover along silicon in vacuum", XIIIth Int. Sym. on Discharges and Electrical Insulation in Vacuum, Paris, France, 1988, p 527-530.

3.- E.H. Rhoderick, Metal-semiconductor contacts, (Oxford: Clarendon Press, 1978), Chapter 2.

4 - M.A. Lampert and P. Mark, Current Injection in Solids, (New York: Academic Press, 1970), Chapter 2.

5.- W. Hwang and K.C. Kao, "Electroluminescence in anthracene crystals caused by field-induced minority carriers at moderate temperatures", J. Chem. Phys. Vol. 58, 3521 (1973)

6.- H.P. Kunkel and K.C. Kao, "Electroluminescence in anthracene crystals under time-varying electric fields", J. Phys. Chem. Solids Vol. 37, 863 (1976)